Abstract

Basic definitions of actor-critic networks along with research papers and how they apply to actor-critic algorithms

RL Technical guide

Table of Contents

[General outlines of critic-actor methods (PPO): 3](#_Toc156312130)

[Actor 3](#_Toc156312131)

[Critic 4](#_Toc156312132)

[Critic influencing the actor 5](#_Toc156312133)

[Flow of data in actor-critic network 5](#_Toc156312134)

[Revisiting Gaussian Mixture Critics in Off-Policy RL 6](#_Toc156312135)

[TLDR: 6](#_Toc156312136)

[Technical points: 6](#_Toc156312137)

[Main points: 6](#_Toc156312138)

[How the paper impacts PPO 7](#_Toc156312139)

[Future work: 7](#_Toc156312140)

[Referenced papers for further reading: 7](#_Toc156312141)

[GMAC: A Distributional Perspective on Actor-Critic Framework 7](#_Toc156312142)

[TLDR: 7](#_Toc156312143)

[Technical points: 7](#_Toc156312144)

[Main points: 9](#_Toc156312145)

[How the paper impacts PPO 9](#_Toc156312146)

[Future work: 9](#_Toc156312147)

[Referenced papers for further reading: 9](#_Toc156312148)

[Multi-Agent RL 10](#_Toc156312149)

[Learning Types 10](#_Toc156312150)

[MARL Algorithms 10](#_Toc156312151)

[*Joint action learning (JAL)* 10](#_Toc156312152)

[Agent modelling 11](#_Toc156312153)

[Policy-based learning 11](#_Toc156312154)

[Regret matching 11](#_Toc156312155)

[Neural Networks in MARL 12](#_Toc156312156)

[Feedforward Neural Networks 13](#_Toc156312157)

[Deep reinforcement learning 13](#_Toc156312158)

[Incorporating neural networks into RL 13](#_Toc156312159)

[Moving target problem 14](#_Toc156312160)

[Correlation of experiences 15](#_Toc156312161)

[Some terminology 15](#_Toc156312162)

[Correlated equilibrium 15](#_Toc156312163)

[Nash equilibrium 15](#_Toc156312164)

[ɛ-Nash equilibrium 16](#_Toc156312165)

[Pareto-Optimality 16](#_Toc156312166)

[Welfare-optimal 16](#_Toc156312167)

[Fairness-optimal 16](#_Toc156312168)

[Regret 16](#_Toc156312169)

[Zero-sum game 16](#_Toc156312170)

[Stochastic 16](#_Toc156312171)

["Conditioned on the state" 16](#_Toc156312172)

[Value of information 16](#_Toc156312173)

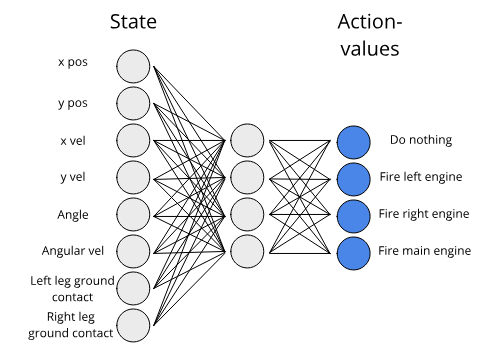
[Neural network 17](#_Toc156312174)

[Deep RL 18](#_Toc156312175)

# General outlines of critic-actor methods (PPO):

### Actor

* The actor network refers to the neural network that is made up of different weights and biases that map states to actions. The below shows an actor network with the states as inputs into the network. As the state is passed through the network the network will output a command based on the previously learned state and action that was taken. The policy needs a way to update how well it is choosing such actions which brings in the Generalized Advantage Estimator ([GAE](https://arxiv.org/pdf/1506.02438.pdf)).
  + The basis of the advantage function (from GAE) is to update the policy based on the action that was taken. This is done by choosing an action and observing what the reward is from that action and comparing it to the mean of actions that has been taken over time. In other words, the advantage function measures whether the action taken is better or worse than the policy’s default behavior which has been learned overtime.
    - I.e. if the drone is on the ground and the actions it can take are (where I denotes motor on and 0 denotes motor off for simplicity):
      * Motor 1: I Motor 2: 0 Motor 3: 0 Motor 4: 0
      * Motor 1: I Motor 2: I Motor 3: 0 Motor 4: 0
      * Motor 1: I Motor 2: I Motor 3: I Motor 4: 0
      * Motor 1: I Motor 2: I Motor 3: I Motor 4: I
    - If overtime the drone learns to do action 4 (all motors on) then if, for example, it takes action 2 and only turns on two motors this action will have a lesser reward compared to that of action 4. This would tell the policy to lessen this weight/bias towards this action and decrease the likelihood of taking this action in the future.
  + Updating the actor is essentially moving its probability mass towards higher quality actions



* In a technical sense, the GAE is using a discounted estimation of k number of advantage functions into the future to gather information on how the current action taken could lead to a plethora of different states and actions taken in the future.

### Critic

* The critic network refers to a neural network that is predicting the cumulative discounted reward of the state-action pairs. This is the **value function** that is learned by the critic and uses the mean squared error as the loss function to optimize.
* The critic network is updated by the Temporal Difference error method which does the following:
  + At a state S predict the return for a given action which includes the reward and the discounted cumulative reward (total reward for a given action)
  + Step into the next state with this action
  + Retrieve the reward and the discounted cumulative rewards with the old policy
  + Calculate the difference between the predicted value and the actual value of the above

How much the value function was off

Returns

Returns

Go to next state Sk+1

By action ai

Reward

Reward

Update value prediction by a factor alpha

Update

Returns

Reward

* The method of TD estimation replaces that of a monte carlo approach which entails sampling every action for the next state along with all subsequent states and actions therein after. The TD estimation can be projected for the next state only (TD(0)), the next two states (TD(1)), or for many states (TD(λ)) which can converge at large amount of states to that of monte carlo. The benefit of having the hyperparameter lambda is to be able to emphasize different segments of training.
  + For example, if having an agent that learns from more recent events then a TD(0) method would be used as compared to a method that would focus on the past experiences of the agent would be TD(1) which becomes more akin to the monte carlo method.
  + TD(λ) where λ is a hyperparameter [0,1] allows for emphasis of each method.

### Critic influencing the actor

* A main idea of the actor-critic dynamic is that the critic network can help to guide the actor network in policy guidance. This is done via the GAE as mentioned above.
* The loss function of the overall algorithm = policy\_loss + value\_loss
  + The policy\_loss is influenced directly by the critic network by the GAE
  + The GAE uses the estimated cumulative rewards from the critic and compares it to the immediate rewards given by the policy to update the policy

### Flow of data in actor-critic network

State and Action:

* The agent observes a state (S) and selects an action based on its policy
* Trajectory for Critic Network:
  + A certain number of future states (a trajectory) are considered for evaluating the value distribution. This trajectory is influenced by the chosen action and the policy.
* Critic Network Calculates Value Distribution:
  + The critic network estimates the value distribution at each state, which is modeled as a mixture of Gaussian distributions
  + Each Gaussian is characterized by a mean, a variance, and a weight
* Network Outputs for Mixture Components:
  + The mean can be a direct output from the neural network
  + The variance is typically output from the network and passed through a Softplus activation function to ensure it's positive
  + The weights are output from the network and passed through a Softmax activation layer to ensure they sum up to one and form a valid probability distribution
    - Example: For 3 Gaussians, the network would output 9 values (3 means, 3 variances, 3 weights), assuming a simple architecture where the output layer directly represents these parameters.
* Network Architecture:
  + Network architecture example: takes an input observation (e.g., a 25-dimensional array from the drone), processes it through layers (e.g., two layers with 64 units each), and outputs 9 values to represent the parameters of the 3 Gaussians for the value distribution
* Comparison of Predicted and Actual Distributions:
  + This comparison is used to compute a loss that measures the discrepancy between these distributions
* Policy and Critic Update:
  + The policy is updated using a method like the Generalized Advantage Estimation (GAE), which helps in balancing bias and variance in the advantage estimates
  + The critic is updated by minimizing a loss function, such as the Cramér distance, which measures the distance between the predicted and empirical distributions
* Loss Function for Critic:
  + The Cramér distance is a suitable choice for comparing distributions as it is sensitive to the difference in shapes between the predicted and empirical distributions, leading to more effective learning of the value function.

# [Revisiting Gaussian Mixture Critics in Off-Policy RL](https://arxiv.org/pdf/2204.10256.pdf)

## TLDR:

* Improves critic performance by better representation learning
* Initial scaling of gaussian components impacts performance while number of gaussians and location initialization does not (initialize at the origin)
* The use of cross-entropy as a loss function proves to not be a norm and therefore does not guarantee contraction for the Bellman operator
  + Plan to try to use the 2-Wasserstein and Cramèr distances instead

## Technical points:

* The Wasserstein metric is not used due to the Bellman Operator not being a gamma-contraction which means the resultant value distributions are not guaranteed to be minimized in distance from each other
* Uses mixture of gaussians to parameterize the distribution Zπ because MoG can be sampled from and has a differentiable log-probability density function
* Neural network Zθ to approximate Zπ(s,a) and use Zθ(bar) as a target network to estimate bootstrap targets to stabilize Q-learning
  + Z replaces the value function V
* Utilizing a distributional loss approach by applying the Bellman operator to the distribution
  + The Bellman operator is a means of shifting the distribution and / or reshaping the distribution so as to compare the returns of an action compared to its successor actions in a specific state (i.e. how much different is the distribution compared to what it previously was at this state)
* Use of the cross-entropy loss to measure the distance between the model’s predicted returns given an action and the actual returns given an action using unobserved next actions according to the policy
  + –(1/B)\*∑H(E[a′∼π​[r+γZθˉ​(s′,a′)],Zθ​(s,a))]
    - Zθ​(s,a)) is the model’s prediction
    - r+γZθˉ​(s′,a′) is the actual returns
  + Other papers highly recommend Cramèr distance instead since it creates unbiased sample gradients whereas the Wasserstein creates biased sample gradients

## Main points:

* On simple environments the MoG approach performed the same as C51 (categorical distribution) and the non-distributional approach (using a scalar value of mean squared error)
* Performs better than or similar to its categorical counterpart C51 and outperforms non-distributional in every category of complex environments
* The increase in performance compared to the non-distributional approach is from 1.) the learning of features by the MoG and 2.) the adaptive reweighting of instances (better learning of the value distribution)
* Tested 1,3,5, and 10 MoGs to see that there is a somewhat diminishing return after going from three gaussians on upward. One gaussian to three was the biggest jump in performance while 3,5, and 10 performed similar
* Initial scaling of the mixture components does seem to impact performance where 1 performs the worst and 0.0001 performs the best out of all the tests

### How the paper impacts PPO

* Changes the critic’s value function to a value distribution
* Instead of using MSE as a loss function for the value function uses the cross-entropy loss to measure the distance between the predicted value distribution and the target (actual) value distribution
* Changes the loss function of the critic network that involves the cross-entropy loss and the distributions as mentioned above

## Future work:

* Using the 2-Wasserstein and Cramèr distances as loss functions

## Referenced papers for further reading:

* GMAC: A Distributional Perspective on Actor-Critic Framework
  + Uses PPO and the Cramèr distance

# [GMAC: A Distributional Perspective on Actor-Critic Framework](https://arxiv.org/pdf/2105.11366.pdf)

## TLDR:

* Improves critic performance by better representation learning; their sample replacement methodology is to have a “n-step return” method but with distributions instead of a trajectory of expected values

## Technical points:

* The value distribution is learned through the distributional Bellman Operator (Ϯπ)
  + The Bellman Operator is only a fancy way of saying the value distribution is moved such that the predicted distribution becomes the actual distribution by continuous updates that maximize the possible value by sampling states and their respective actions
    - The Bellman Operator, in this case, **only updates** the predicted value distribution
    - This is merely a way for the critic network to update its predictions where the Bellman target is the actual value distribution
  + Instead of sampling all possible next states and actions Z(X’, A’) which would lead to infeasibility issues, this paper instead approximates the next state value distribution Z(X’)
    - This makes sense since the PPO algorithm uses the next state’s value estimate and not the state-action value estimate
* Transferring a scalar reward to a distributional reward provides more information for the neural network to learn on (behavior and characteristics of the value distribution)
  + i.e. the preservation of multimodality
* Uses mixture of gaussians to parameterize the distribution Zπ because MoG can be sampled from and has a differentiable log-probability density function
* Uses a “Sample-Replacement” algorithm which has the basis of turning the Temporal Difference method from a scalarized value to a distribution
  + This is done by transferring the target value (current reward + discounted reward) to the target distributional value (current reward + discounted distributional reward)
    - The discounted distributional reward is a little difficult in that taking the expectation of the future rewards does not give a scalar as is normal, but instead gives the expectation of multiple distributions
    - Therefore, this is handled by taking a weighted sum of the multiple distributions, since the expectation is a linear operator, to give the final cdf of the discounted value
    - This gives the appropriate TD(λ) of the distribution
    - To mitigate taking the infinite trajectory of each state, the truncated sum is often used given a desired trajectory length of N
  + Reduce the need to compute N2 different distributions by first estimating the probability distribution
* The Cramèr distance comes into play for telling how far apart the empirical distribution and the approximated distribution is
  + Since the Cramèr gives an unbiased sample gradient we can use stochastic gradient descent to minimize the distance between the two
  + The squared Cramèr distance is equal to one half of energy distance
* Stuck point:
  + For equation (11) what exactly is meant by having a mixture of distributions? For each step of the sum it is the reward of that state plus the discounted value distributional reward which is fixed for each increment….actually the fact is that for each increment of the sum a different reward is added so now we have multiple reward distributions since it is adjusting each distribution of the incremental sum by R
    - So therefore, taking the expectation of Zt(n) would be taking the expectation of n many different distributions which is an expectation of random variables of random variables

Trajectory of states where each state is a step into the future

State 3 (unobserved)

Z(3)\_3 = γ2R(x3)

Repeated distributions

State 2 (unobserved)

Choose action

Z(2)\_2 = γR(x2) + γZ(x3)

Z(1)\_1 = R(x1)

Z(2)\_1 = γR(x1) + γZ(x2)

Z(3)\_1 = γ2R(x1) + γ2Z(x3)

State 1 (unobserved)

* Solution for above stuck point
  + They come up with a trajectory of states sampled from the policy (let’s say 3)
  + For each of these three states there will be distributions calculated as follows:
    - State 1 will have three distributions: S1 (itself), S1 🡪 S2, S1 🡪 S3
    - State 2 will have two distributions: S2 (itself), S2 🡪 S3
    - State 3 will have one distribution: S3 (itself)
* Consider the parameterized model of the value distribution as a MoG (mixture of Gaussians)
  + Zθ(xt) ∼ ∑K wi(xt) N(z|µi(xt), σi(xt)²), where ∑K wi(xt) = 1
  + The energy distance has the following form (related to Cramèr)
    - E(U, V) = 2δ(U, V) - δ(U, U₀) - δ(V, V₀)
      * Where δ(U, V) = ∑\_(i, j) wui wvj E[|Zij|],
      * And Zij ∼ N(z|µui - µvj, σ²ui + σ²vj)
  + Analytical approximation of the empirical distribution can be done as follows
    - Zt(λ) = (1/m)
* For producing the MoG distribution itself
  + Mean was left as the output of the network
  + Variance output was run through a softplus layer
  + Weights were run through a softmax layer (so their sum is 1)

## Main points:

* Compare the empirical approximation (given by an analytical/observed mixture of Gaussians) to the predicted value distribution given by the SR(λ) which is the same ideology of TD(λ)
* To calculate how different the actual to the predicted distribution is they use the modified Cramèr distance and work to minimize this as the loss function
* Advantage function is remained unchanged - expectation of the value distribution
* Able to capture multimodality within the value distributions
* Reduce computational cost by using the sample-replacement method

### How the paper impacts PPO

* Changes the critic’s value function to a value distribution
* Changes the loss function to
  + L = Difference between predicted and actual mixture of Gaussian distributions – difference between predicted distributions – difference between actual distributions

## Future work:

* “Further development of these ideas as future works…”

## Referenced papers for further reading:

* [Statistics and Samples in Distributional RL](https://arxiv.org/pdf/1902.08102.pdf)
  + Demonstrates how to take in a collection of values for certain statistics and return a probability distribution with those statistic values

# Reinforcement Learning

## Learning Types

* Central Q-learning (CQL): a single central policy (πc) is trained by observations of all agents and chooses actions for each by selecting joint actions
* CQL Problems:
  + Scalarization of zero-sum and general-sum stochastic games
  + Action space grows exponentially with a policy learning joint actions given an increase in actions and / or agents
  + Physically / virtually distributed so hard to communicate from πc to agents and vice versa
* Solutions to CQL Problems:
  + Decompose πc into multiple policies given the respective state (specific states of learning can have different policies)
  + This is achieved by giving each agent a copy of πc and the agent will then compute its own action from a joint action
* Independent learning (IQL): a policy for each agent while it ignores the other agents
* IQL Problems:
  + Each agent learns from its own policy using only its local history and therefore misses out on information that is trained on by other agents
  + No use of agents’ information which makes for a dynamic environment that is always changing
  + Transition function state non-stationarity where the other agents update their own joint actions which causes unstable learning
* Solutions to IQL Problems:
  + Self-play: all agents use the same policy and compete against itself to get better
  + All agents have the same learning rule which helps reduce some of the non-stationarity problem

## MARL Algorithms

### Joint action learning (JAL)

* Uses Temporal Difference learning to learn estimates of joint action values
  + Address the IQL problem of non-stationarity of other agents and the CQL problem of reward scalarization
  + Learn joint action value models that estimate the expected returns of joint actions in any given state
  + JAL-GT focuses on viewing the joint action values as a non-repeated normal-form game for a state

##### Minimax Q-learning

* + When to use it: in two-agent zero-sum stochastic games where each agent has all relevant information, and both agents have perfect information (i.e. all possible information)
    - Good for competitive environments
    - Minimax is particularly good at making short-term tactical decisions where the immediate consequences of actions are more critical than long-term strategy
    - Bad when not all relevant information is known to all agents which causes exploitation of agents
* Policies learned do not necessarily exploit weaknesses in their opponents, but these policies are robust to exploitation by assuming worst-case opponents during training

##### Nash Q-learning

* When to use it: in a general-sum stochastic game with a finite number of agents
* Computes a Nash equilibrium solution given a general-sum game
* Guaranteed to reach an equilibrium point under very restrictive circumstances
  + Must try all combinations of states and joint actions

### Agent modelling

* learning explicit models of other agents to predict their actions based on their past chosen actions

##### Policy reconstruction

* + aims to learn models of the policies of other agents based on their observations of past actions (supervised learning problem using the past observed state-action pairs)

##### Fictitious play

* + Each agent i models the policy of each other agent j as a stationary probability distribution by taking the empirical distribution of j’s past actions which means it is *not* conditioned on the state, but rather past actions
  + Each agent i tries to choose their action to maximize the overall reward given the other agents j actions from previous steps

πj(aj) = (number of times agent j selected action aj) / (all possible next actions)

##### JAL-AM

* + Combination of Joint Action Learning (JAL) and Agent Modelling (AM) which combines
    - Aspects of learning the joint action values using temporal difference learning (from JAL)
    - With the agent model of other agents’ policies and best responses to select actions for the learning agents and to derive update targets for the joint action values
  + Like fictitious play, but the empirical distribution is now conditioned on the state

πj(aj|s) = (number of times agent j selected action aj in a given state) / (all possible next actions in a given state)

* + Looks at all possible actions in a state and picks the action that will give maximal value given the joint action value and the other agent’s empirical distributions
  + Therefore, this method will give *best-response* *actions* compared to ­*best-response* *policies*

### Policy-based learning

* learn policy parameters using gradient-ascent techniques

### Regret matching

* minimize different notions of regret and can achieve no-regret outcomes

## Neural Networks in MARL

* Neural networks are good generalization techniques which is good for agents in the sense that they can generalize their actions and do not need to go to a given state to learn from it
* Each scenario / game played has a certain value function in which is the “optimal” reward pathway for an agent to act
  + A neural network can change its weights and biases to map closer and closer the actual value function by iteratively going over possible actions in states
  + This ability for the neural network to change its weights allows for it to ultimately to “find” the target value function without us knowing it
  + Imagine the maze below in which a person is trying to fight their way through a forest for a quest
    - As the agent moves within the environment they encounter energy depletion, potential restore points, and potential harm
    - Inherently, there is an “optimal value function” where a person will be able to make their way through this forest and complete the quest with the highest energy level possible and the least amount of harm possible
  + A neural network can estimate this “optimal value function” and generalize its learning much faster compared to tabular methods
    - This is done by learning some function f(x;θ) for some input x∈Rdx
      * We take some input value x and multiply it by some value θ which can be a weight in terms of a neural network
      * v̂(s;θ) = θTx(s) = sum(θk\*xk(s)) where θ denotes parameters and x(s) represents the state features
    - We can then compare the target estimation the neural network learned compared to the actual value function (given by TD learning) and minimize this difference as our loss function

Energy level

Restore

### Feedforward Neural Networks

* Also called feedforward networks, fully-connected neural networks, or multilayer perceptrons (MPLs)
* Comprised of weights and biases that are ran through an activation function
  + *fk*,*u*​(*x*;*θku*​)=*gk*​(**w**⊤*x*+*b*)

A picture containing text, gauge, device

Description automatically generated

* Activation functions are used in neural networks to cause non-linearity
  + i.e. the composition of two linear functions is a linear function
  + Taking a linear function and passing it through a non-linear function gives a non-linear function
* Since there is no closed-form solution to solve the perfect weight / bias of a neuron there exists non-convex gradient-based optimization methods to help with optimizing each weight / bias
  + Gradient-based optimization involves
    - Loss function L(θ) – a way to give the network a guide on what to minimize
    - Gradient-based optimizer – which optimization technique to use
    - Backpropagation – a way to compute gradients in the network
      * [Source](https://www.youtube.com/watch?v=VMj-3S1tku0) for understanding backpropagation

Diagram, text

Description automatically generated

* Recurrent neural networks are designed to process sequential data

## Deep reinforcement learning

### Incorporating neural networks into RL

* The incorporation of neural networks into value function approximation involves a few challenges, but has great benefits
  + In continuous action spaces it will be unlikely that a drone will encounter the same state and therefore these neural networks can generalize for us the value function of unseen states
  + The drawback is now we must implement the correct architecture, a loss function, and a gradient-based optimizer
* We can then transition the value function from a tabular method to a neural network by having the neural network receive the state (s) as an input and output the action-value estimates for every possible action Q(s,an)
  + For explicitness it will return a set of rewards for possible actions such as:
    - Q(s,a1) = 100, Q(s,a2) = 45, Q(s,a3) = 5, Q(s,a4) = 90

Icon

Description automatically generated with medium confidence

* Loss function in this case is still the squared difference between the target value yt and the predicted value function estimate Q(st, at; θ)
  + L(θ) = (yt - Q(st, at; θ))2
  + This loss function is minimized by changing the network parameters θ using the same experience through a single state transition
  + It is important to notice that the neural network estimated value function will be seen twice in this loss function
    - Q(st, at; θ) for the current state’s reward
    - yt = Q(st+1, a’; θ) for the target value function
  + The target value function must **not** have the backward pass compute and update its gradient (modern deep RL libraries take this into account and give ways so this gradient is blocked) and is only used as an estimation target value function
* Key point (at least for me): the network parameters do not change on a per state basis, but rather the connection strength is what dictates different actions per different states
  + i.e. you can freeze the network weights and the drone will still fly on its on because it learns over hundreds / thousands of parameters to generalize different states

### Moving target problem

* The moving target problem is a problem in which the policy is adapting based on time
  + As the policy changes during learning the update target becomes non-stationary since the value estimate sued in the target is also changing
  + This is now exacerbated since we are approximating the value function with neural networks
    - All states and actions change continually as the value function is updated
* Combining off-policy training, with bootstrapped target values, and function approximations by the neural network can cause a *deadly triad* problem where the values of random actions can be overestimated and not get corrected which causes divergence
  + On-policy methods can fix this because an agent can visit a state and update its value function overestimation to a more correct (more correct because it is small updates at a time)
* Another way to help fix this problem is to create a neural network that will have the same architecture of the main value function, but instead it will compute the bootstrapped target values
  + The target network is initialized with the same parameters as the value function estimation network and has parameters
  + Yt = rt + ɣmaxa’Q(st+1, a’; ) where Q(st+1, a’; ) will be the target network
  + Instead of performing gradient descent on the target network, the parameters are periodically copied from the current value function estimation from the neural network
    - Why: because we don’t want the target network to diverge too far from the current network
    - However, this does help with target stability

### Correlation of experiences

* The data used to train such networks is assumed to be i.i.d. (identically and independently distributed) which is mainly false in many RL forms
  + Samples are the experiences of the drone given the tuple of state, action, reward, next state which are highly correlated
  + Changes in policy change the distribution from which the experience are pulled from
* Correlations are important in the sense that if an agent learns a certain behavior, it might become specialized in the particular action and its value function parameters learn this behavior
  + If the agent has any change of state (say the drone was always initialized from the right of the objective so it learned how to land from the right and now it has a sudden initialization from the left) then it might fail since it has now changed the direction from which is it trying to land, and the value function will provide incorrect estimations
    - To mitigate this issue we can add a replay buffer D which takes random experiences and stores them in this buffer
      * D = {(st, at, rt, st+1)}
    - Then we get a batch B of this buffer data uniformly and train the value function on this
    - **Key point:** the MSE is computed over the batch and minimized to update the parameters of the value function
    - **Note:** this is an off-policy method since the batch can contain experiences from the policy from recent timesteps as well as earlier timesteps

## Common algorithms

### DQN (Deep Q-networks) / Rainbow

* Uses a neural network to approximate the value function
* DQN uses a target network and replay buffer to mitigate against the moving target problem and correlation of consecutive samples
  + Both of which are pertinent to effective learning
* Issue with DQN: overestimation of action values since the target network computation uses the maximum action-value estimate over **all** actions in the next state where
  + maxa’Q(st+1, a’; ) where this maximum action is likely to pick an action that is overestimated
  + This overestimation issue can be fixed by decoupling the greedy action and the value estimation
    - Which in simple terms is the main value function asking, “which action should I take?” and the target value function asking, “how good is that action?”
      * yt = rt + ɣQ(st+1, argmaxa’Q(st+1, a’; θ);)
* Double DQN addresses the problem of value overestimation by the above-mentioned decoupling of the greedy action and the value estimation
* Rainbow incorporates six extensions of DQN: decoupling of value overestimation, prioritized replay, dueling networks, multi-step learning, distributional RL, and noisy nets

Text

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### Policy-Gradient Algorithms

* Learning a policy as a parametrized function which can be represented using linear function approximation
* These methods compute gradients with respect to the parameters of their policy and update the learned policy
  + By transferring the policy to a learned neural network this will allow for us to use policies in the continuous action space
* Basis of the policy: receives a state as the input and outputs a scalar output for every action l(s,a) to represent the policy’s action preference in a given state
  + These scalars are transformed into a probability distribution using the softmax activation function
    - Π(a|s; ϕ) = el(s,a; ϕ) / sum(el(s,a’; ϕ))
    - Where this is the current policy’s single action / the sum of all actions in a state
    - ϕ is policy parameters and θ is value function parameters
* The policy can be update via a loss function optimization in which the learned parameters increase the “quality” of the policy
  + A measure to quantify a “good policy” is the expected episodic returns which can be represented by the value of the policy in a given state Vπ(s) or the action value Q π(s, a)

#### Policy-gradient theorem

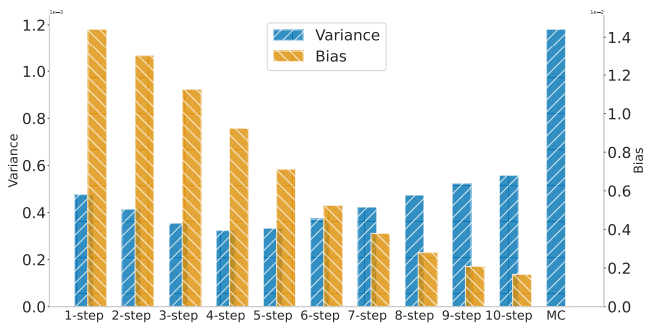
* Instead of minimizing a loss function as with many neural networks, the policy-gradient theorem uses a different methodology of maximizing a state-visitation gradient of the policy
* Cannot use a replay buffer to update the policy since its expectation shows that it uses the data is generates, so if it uses old data it will be learning “bad habits” therefore it has to be on-policy



* The numerator represents the gradient of the policy pointing in the direction in parameter space that most increases the probability of repeating action a on future visits to state s
* The denominator is a normalization factor to correct for the data distribution by the policy

### Actor-Critic Algorithms

* Family of policy gradient algorithms which train a parameterized policy (actor) and a parameterized value function (critic)
  + Compared to monte carlo methods, these methods use bootstrapped value estimates to optimize policy gradient algorithms
* Bootstrapped returns is an important part of these algorithms as it has two primary benefits
  + Estimate episodic returns from a single step rather than from a history of episodes
  + This method also provides *less variance* as compared to monte carlo methods since the bootstrapped returns **only depend on the current state, action, reward, and next state** but does induce an *increase in bias* however this tradeoff has shown to increase training stability
    - Whereas monte carlo methods depend on the history of the episode
  + The below graph represents the tradeoff between bias variance as once projects the returns from 1 single bootstrapped step to monte carlo
    - The takeaway is that a balance between methods can have moderately low levels of each bias and variance



#### A2C: Advantage Actor-Critic

* Uses the advantage function to compute estimates of which direction for the policy gradient to go
* The advantage function is given by Aπ(s,a) = Qπ(s,a) – Vπ(s) = rt + ɣV(st+1) – V(st)
  + Where Q is action-value and V is state-value functions with respect to the policy
  + For the policy π, the action value Qπ(s,a) = rt + ɣV(st+1) is the expected returns of π when first applying action a in state s and afterwards following π
    - 🡪i.e. returns(action🡪new state🡪trajectory of policy)
    - The immediate rewards of the policy’s action
  + The state value Vπ(s) = V(st) is the expected return when following the policy π already in a given state without following a predetermined action
    - 🡪i.e. returns(next state🡪trajectory of policy)
    - The bootstrapped rewards of a state
  + The advantage function asks the question: how much better or worse is an action compared to that of an average action taken by the policy?
    - 🡪 returns(action🡪new state🡪trajectory of policy) - returns(next state🡪trajectory of policy)
    - Positive advantage: increase the probability the policy will choose the action again
    - Negative advantage: decrease the probability the policy will choose the action again
  + ***Key point about distributional RL:*** You do not have to update this to be the value distribution since this is for policy optimization and the main point of distributional RL is for the critic network to learn its value distribution better
    - Now this *could be* implemented but I am not sure how you could accurately compare the action value Qπ(s,a) to that of the distribution without having to have Qπ(s,a) as a distribution as well
      * One thought is to only return the mean of the value distribution (which is already being done)
      * Another thought is to make a mixture of Gaussians, weight them, make a final representative distribution and take the mean (I think this will just give the same mean as before)
      * Or take the mode of the mixture of Gaussians instead of the mean to handle multimodality
  + We can reduce the variance of the advantage function by introducing the n-step returns (as above between 1-step bootstrapped methods and monte carlo)
  + ***Main point:*** We now have a loss function we can optimize with regards to the advantage function (we can minimize it by making it negative)
    - L(ϕ): -Adv(st,at)logπ(at | st; ϕ) to update actors parameters
    - The loss of the critic network can also be calculated from part of this by
      * L(θ): (yt – V(st; θ))2 to update critic parameters
      * Where yt is the bootstrapped target yt = rt + ɣV(st+1; θ))
* An additional element of this algorithm is the addition of the cross-entropy term which is a measure of the policy’s uncertainty
  + If all actions have a uniform distribution, then this is maximal uncertainty
  + Maximizing the entropy provides a regularization term that discourages premature convergence to a suboptimal close-to-deterministic policy and hence incentivizes exploration

#### PPO: Proximal Policy Optimization

* The problem with A2C is any gradient step (even with small learning rates) can lead to significant changes of the policy and could reduce the expected performance of the policy
  + This can be mitigated by creating “trust regions” which create regions for the actor’s parameters that will not lead a significant reduction in performance
* PPO builds on the idea of TRPO (as seen below) by having trust regions for policy optimization introduced by sampling weight ρ which is a surrogate loss function
* These sampling weights are a measure of how good the current policy is compared to that of the old policy i.e. the expected returns of the current policy in the numerator and the expected returns of the old policy in the denominator
  + This helps to show how much better/worse the new policy is and updates accordingly
  + Ρ(s,a) = π(a|s;ϕ) / πβ(a|s)
    - π(a|s;ϕ) is the policy that we wish to optimize parameterize by ϕ
    - πβ(a|s) is the behavior policy which was used to select action a in state s (or the “old” policy)
  + This method allows for the policy to be updated multiple times using the same data
* In code the loss function for the policy can be seen as:
  + pg\_loss1 = -mb\_advantages \* ratio
  + pg\_loss2 = -mb\_advantages \* torch.clamp(ratio, 1 - args.clip\_coef, 1 + args.clip\_coef)
  + pg\_loss = torch.max(pg\_loss1, pg\_loss2).mean()

##### TRPO: Trust region policy optimization

* Constrains each optimization step of the policy to a certain region to reduce the risk of any degradation in quality of the policy and therefore create gradual and safe quality of steps to improve the policy
* The downfall of TRPO is that is requires solving one of two problems
  + The constraint that is implemented onto the policy
  + Computing a penalty term

# Multi-agent RL

* The main question of MARL is: what information can agents use to make their action selection?
  + Or what information can agents use to condition their policy on?
  + Decentralized policies say that agents can only learn from their own local history
  + Centralized policies say that agents can learn from other agents’ local history as well

## Centralized Training and Execution

* Shared information between agents can include local observation histories, learned world and agent models, value functions or even other agent policies
* This approach means that we reduce the multi-agent problem to a single agent problem where one policy is learning actions to tell each agent which action to take
* The benefit of using a centralized policy is during partial observation environments or complex coordination between agents where now the policy can “fill in” some of the blanks in the environment
* The downfall of centralized learning is:
  + Scalarizing joint rewards across all agents which might be near impossible for zero-sum games
  + The joint policy must learn over the joint action space which grows exponentially with each agent that is added
  + Communication between agents is not possible in all cases

### (CTDE) Centralized training with decentralized execution

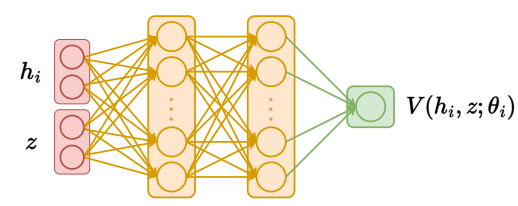
* Use centralized training to train agent policies, but execute in a decentralized manner
  + Utilizes the local information of all agents to update the agent policies
  + Each agent’s policy only requires the agent’s local observation to select actions
  + i.e. the policy of each agent is decentralize and they learn from their local history only, but the critic is centralized and is conditioned on the joint observation history and therefore provides better value estimation to their individual policies

#### Multi-Agent Policy Gradient Theorem

* Extending the single agent policy gradient theorem to a multi-agent setting is a matter of considering that the expected returns of each agent is dependent on the policies of all the other agents
  + Meaning that the actual rewards received over time is a function of the other agent’s and their actions taken in the environment (since the actions come from the policy then directly the returns are dependent on the policies of the other agents)
  + The policy gradients can be represented as follows:
    - ∇ϕiJ(ϕi) = E[Qiπ(, ‹ai,a-i›)∇ϕilogπi(ai|hi = σi(); ϕi)]
      * The gradient in this case is not a new equation, but the authors are being explicit that when this is implemented into code this is what happening during the optimization step
        + In our case, we will have the loss function and still optimize the loss function by minimizing the loss, but from a theoretical standpoint this is the notation

#### Centralized Critics

* Conditioning the policy on the local history of the agent only ensures decentralized execution since there is no information coming from outside the agent π(hit;ϕ)
* Conditioning the critic on all the information from each agent is generally an okay idea since after the training is done, the critic is discarded altogether and only the policy is needed to make decentralized actions
  + The value function conditioned on the observation history of all agents given its current neural network parameters θi : V(h1t, … , hnt; θi)
* We can add a vectorized parameters (z) in which we can pass any sort of inaccessible information such as the full state of the environment and any external data



* I think in this case we could even use image data from each of the agents in which we could incorporate something like [SuperGlue](https://psarlin.com/superglue/) here as z
  + The loss of this new centralized critic becomes
    - L(θi) = (yi – V(hit, zt; θi))2 where yi = rit + ɣV(hit, zt; θi)
  + However, doesn’t this mean that by using the advantage function that inherently the policy is being influenced by outside observations?
    - Yes, this is correct, but this is only during the training phase and once training is over the agent only has its local history to influence its actions when the critic is no longer used
    - So, inherently the policy and the critic network are being influenced by the other agent’s histories during the training phase
* Centralized critics conditioned on the history of the agent and external information can stabilize training particularly in partially observable multi-agent environments

#### Centralized Action-Value Critics

* The value function of each agent is conditioned on the observations and actions of each individual agent
* Policy: conditioned only on the local observations of each agent
  + Though the advantage function still influences the policy for simplicity we will say the policy is only conditioned on its own history
  + L(ϕi): - Q(hit, zt, at; θi)logπi(ait | hit; ϕi) for each agent i
* Critic: conditioned on its own local history, the external information, and the next actions taken by all agents
  + L(θ): (yt – Q(hit, zt, at; θi))2 where yi = rit + ɣQ(hit+1, zt+1at+1; θi)
    - hit its own local history
    - zt external information
    - at all other agents’ actions beside agent i
    - θi neural network parameters for the critic to estimate the value function

Diagram

Description automatically generated with low confidence

* Instead of calculating values of all joint actions across all agents, this method will use the actions of other agents as input and output a scalar value based on these as inputs
  + This is done to drastically reduce dimensionality whereas evaluating all the joint actions would lead to an exponential increase in dimensions

#### Counterfactual action-value estimation

* In the above we used a state-action value estimate to see what the direct impact of an action would be that helped ***fix the multi-agent credit assignment problem***
  + We did not use a state value estimation, but this can still be used as a part of the advantage function estimation
* The *difference rewards* between the received reward and the reward agent i would have received if it had chosen a different action i can aid in the multi-agent credit assignment problem
  + di = Ri(s,‹ai,a-i›) - Ri(s,‹i,a-i›)
  + However, since this requires a “default action” there isn’t a best way to compute this from the reward function itself
  + We can, however, use the expectation of the agent’s current policy as the default action and use the *aristocrat utility:* di = Ri(s,‹ai,a-i›) – E[Ri(s,‹ai’,a-i›)]

#### Individual-Global-Max (IGM) Property

* The process of breaking down the overall global reward system into an agent’s individual contribution (its utility function) to the global reward system
  + Two major implications
    - Each agent can follow its own greedy policy with respect to its own utility function to allow for decentralized execution where each agent selects the *greedy joint action*
    - The target value can be obtained by computing the greedy individual actions of all agents with respect to their individual utility function

##### Linear Value Decomposition (not practical)

* The simplest method to decomposition rewards is using a linear decomposition where the global reward is the sum of each agent
  + rt = 1t + … + nt where each it is the utility of each agent at timestep t
    - Each utility is obtained by the decomposition and is therefore does not represent a true reward from the environment

##### Value Decomposition Networks (VDN)

* Maintains a replay buffer D containing the experience of all agents and joint optimizes the loss function
* L(θ): sum∈B (rt + ɣmax∈A Q(ht+1, a, ) – Q(ht, at; θ))2
  + Where ɣmax∈A Q(ht+1, a, ) is the actual return of an action for each agent
  + And Q(ht, at; θ) is the predicted value of each agent’s action
  + The point: the value function is learning the decomposed value function (which is a global value function) of all the agents by using the sum of their respective actions in an overall target / value estimation

Agent 1

Agent 2

Agent 3

Utility Function

Utility Function

Utility Function

Neural network

Neural network

Neural network

Neural network

Δ(actual-predicted)

Obs(0)

Obs(1)

.

.

.

Obs(99)

Obs(100)

D =

Obs(15)

Obs(27)

.

.

.

Obs(65)

Obs(96)

B =

Replay buffer with N samples

Choose random batch from buffer

—Local to the agent

—Global network

##### Monotonic Value Decomposition (too restrictive)

* The name QMIX represents an agent’s network and the overall mixing network that combines each agent’s network into Qtot
* QMIX is a centralized action-value function that is approximated by a monotonic aggregation computed by the mixing network which is parameterized by the output of the trained hypernetwork
  + Q(h, z, a, θ) = fmix(Q(h1, a1; θ),…,Q(hn, an; θn);θmix)
    - Multiple the action-value functions together to get an overall action-value function
    - This ensures the monotonicity property

##### QTRAN

* Uses three neural networks to aid in factorizing tasks free from additivity and monotonicity as with VDN and QMIX
  + 1. Network to learn the joint action-value network: Q(h, z, a; θq)
  + 2. Utility functions for each agent: Q(hi, ai; θi)
  + 3. Network to learn the state-value network: V(h, z; θv)
  + Σi∈I Q(hi, ai; θi) – Q(h, z, a; θq) + V(h, z; θv)
    - V(h, z; θv) = maxa∈A Q(h, z, a; θq) - Σi∈I Q(hi, ai\*; θi)

### Joint action learning with agent modeling

* Each agent’s policy, ideally, is conditioned on the policies and value functions of all other agents
  + This ideal is not practical as policies can be much too complex, policies might be available during centralized training but not in decentralize execution, and the policies of other agents change during training
* To overcome these barriers of learning representations of other agent’s policies we can introduce encoder-decoder neural network architectures

#### Encoder-decoder method

* + Encoder-decoder neural networks are often used as sequence-to-sequence architecture
    - In our case, the encoder will take the observation history and output a representation of the policies for each other agent
      * mit = fe(hit; ψie) where fe is the encoder network
    - The decoder network will take this representation of a policy and predicts the action probabilities of all other agents at the current timestep
      * -i i,t = fd(mit; ψid) where fd is the decoder network
  + Every neural network needs a loss function to optimize and therefore the cross-entropy loss is defined by:
    - L(ψie, ψid) = Σ -logj i,t(ajt) with j i,t = fd(fe(hit; ψie); ψid)
* When applied to the level-based foraging environment the centralized A2C + AM considerably outperformed centralized A2C which illudes to the idea that an agent learning the other agent’s policies leads to lower variance and quicker convergence to higher returns
* The next question is: what do each of the agents think about a particular action that agent i did and what do they think about the knowledge of agent i?
  + This is known as recursive reasoning which is implemented using Bayesian variational inference to model the beliefs of agents about the policies of other agents as well as the uncertainty of these beliefs
* Agnostic to the MARL algorithm used to learn the policies of agents

***Encoder-decoder flow path***

* Agent i has an encoder to represent agent j’s policy
* The decoder returns the predicted policy’s probability actions
* Agent j takes an action (actual action)
* This “actual action” is compared to the model prediction probability of this “actual action”
* The loss is the difference between the actual value (100% since it’s a label) and the model’s predicted probability value

Δ(predicted – actual)

Agent i history

Encoder

Representation of other agent’s policy

Decoder

Agent i policy

Predicted policy of agent j

0.09

0.019

0.027

0.139

0.290

.

.

.

0.23

0.012

0.390

0.001

0.089

.

.

.

0.020

0.500

0.002

0.000

0.084

.

.

.

Predicted Agent 1

Predicted Agent 2

Predicted Agent 3

Choose action

Choose action

Choose action

Actual action

Actual action

Actual action

Loss of timestep t

—Agent j

—Agent i

* The encoder representation can be used to condition the policy and the value function of each agent
* Clean RL for policy output

***Gradient flow path***

* The backpropagation step will include updating the gradients in the decoder and encoder networks
  + This will change the policy of Agent i since the gradients are being updated in the encoder network in which the output is given to the agent’s policy as external information along with the history of agent i

Δ(predicted – actual)

Agent i history

Encoder

Representation of other agent’s policy

Decoder

Agent i policy

Predicted policy of agent j

0.09

0.019

0.027

0.139

0.290

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0.23

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0.020

0.500

0.002

0.000

0.084

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.

.

Predicted Agent 1

Predicted Agent 2

Predicted Agent 3

Choose action

Choose action

Choose action

Actual action

Actual action

Actual action

Loss of timestep t

Backpropagation path

#### Environments with homogeneous agents

* Agents share the same or similar capabilities and characteristics which can include history, actions, observations, and rewards
  + Nearly identical agents
* Weakly homogenous agents vs strongly homogenous agents
  + Weakly homogenous agents mean that an agent can take on another agent’s policy and get the same reward as if it was action on its own reward system
  + Strongly homogeneous agents share identical policies
  + Left off on page 276

## Decentralized Training and Execution

* Agents only have access to their own local history, models, and observations

### Independent learning

* Each agent does not model the presence and actions of other agents instead the other agents are seen as a non-stationary part of the environment dynamics
* Each agent trains its policy in a completely local way using single RL methods
  + Benefit of scalability as there is no exponential growth of having many joint actions
  + Downsides:
    - Policies do not leverage information from other agents
    - Training can be affected by non-stationarity caused by concurrent training of agents
    - Agents cannot distinguish the difference between stochastic changes in the environments because of other agent’s actions and the environment transition function

#### Independent Value-Based Learning (IDQN)

* Each agent trains its own action-value function Q(·; θi)
* Maintains a replay buffer Di (as a remember point – this is so that the moving target problem is mitigated by keeping a buffer of state, action, reward, and next state information)
* Learns from its own observation history, actions and rewards using DQN
* The loss function is still L(θ): (yt – V(st; θ))2, but yt in this case is from the agent’s own target network yt = rit + ɣmaxQ(hit+1, ai; i)
  + The critic network is now Q(hit, ait; θi) in which it is only updated on its own history and actions
  + The difference in i and θi still hold that the former is for the target neural network and the latter is for the value function neural network
  + The value function parameters θi are minimized by aggregating the loss of each agent where L(θ1) + L(θ2) + …+ L(θN)
* The downside of using IDQN is the replay buffer could potentially provide a mismatch between observations, actions and rewards
  + Where two agents are in the same state and select the same action, but since their target networks are different, they get different returns for the same state/action

#### Independent Policy Gradient Methods

##### Independent REINFORCE

* The monte carlo version
* Policy gradient methods can be introduced into MARL interpedently per agent
  + Each agent maintains its own policy and learns independently from its own experiences
  + The policy gradient is computed based on the agent’s own actions and rewards not considering other actions or policies taken by other agents
* Each agent’s policy gradient is updated by the expectation of its policy multiplied by the agent’s returns with the gradients being normalized by the inverse current probability of selecting the action under the current policy
  + One benefit of this is the agents individually learn from the most up to date information

##### Independent A2C / PPO

* Implementing this is similar to REINFORCE since each agent is independent, they will use their own experiences to update their own policy
* In a parallelized environment, each agent receives experiences from multiple parallel environments
  + This then gives the problem that the collected experience across all agents and parallel environments form batches of higher dimensionality
  + The observations collected from k environments on a time step t from a two-dimensional matrix where the observation is a function of the timestep and the environment
* The loss in this case is summed over each environment for each agent and divided by the number of environments to get the average loss per environment
  + Policy loss: L(ϕ) = 1/K \*
    - * Where the = advantage \* logπ(action | agent history; ϕi)
    - Sum of each environment’s loss
    - Sum of each agent’s loss over the environments
    - Divided by the total environments to get total loss per agent per environment
  + Critic loss: L(θ|k): (yi – V(hit,k; θi))2 where yi = rit,k + ɣV(hit+1,k; i)
    - Same format as before, but for each environment
    - Clarification point: given the loss function notation of being a conditional probability L(θ|k) I would like to know what is the intersection point between the policy parameters and the kth environment since L(θ|k) = P(θ∩k) / P(k)

Critic Parameters

Kth environment

What does this intersection point represent?

* + - This point, intuitively, seems to be the intersection of the critic parameters such that they minimize the loss across all of the K environments – i.e. we are taking the loss of all the environments and dividing it by the number of environments to get a loss per environment and then minimizing this
      * So, this seems to be fitting the parameters to the general environment and not just picking the best performing parameters across the environments

## Some terminology

### Correlated equilibrium

* allow correlation between policies
  + Each agent knows its own action, but NOT the other’s action
  + Each agent knows the probability distribution
    - The agent cannot deviate to increase their own expected reward

### Nash equilibrium

* applies the idea of mutual best responses to general-sum games with two or more agents
  + Focuses on the fairness aspect of the fairness/welfare ratio (fairness / welfare defined below)
    - If we have an agent i then every other agent in the game is focusing on minimizing the maximized achievable reward by agent i
  + Good to use when agents have a mixture of competitive and cooperative environments
  + In systems where stability is desired Nash Equilibrium provides a point where the system can settle
  + No agent benefits from changing their strategy if others keep theirs unchanged

### ɛ-Nash equilibrium

* relaxes the idea that an agent is not allowed to gain *anything* by unilaterally deviating from its policy
  + Instead, this constraint is relaxed to say the expected return cannot increase by some value determined by the user ɛ > 0 when deviating from its policy in the equilibrium

### Pareto-Optimality

* there is not better joint-policy that improves reward for at least one agent without decreasing the reward of another
  + Every game must have at least 1 Pareto-optimal solution
* Temporal difference learning: iterative way to update the value function
  + i.e. predict the cumulative reward of a state, step into the state and observe the actual reward, and then update the prediction based on how far it was off from the actual

### Welfare-optimal

* a policy that is focused on the maximum expected return possible among all agents

### Fairness-optimal

* a policy that is focused on each agent getting close to similar rewards
  + Ensure magnanimity between agents

### Regret

* difference between reward received and the reward an agent could have received given a different policy
  + No-regret if limit is almost zero meaning that the agent acted in an optimal way
  + Unconditional regret is calculated without assuming any specific condition or state of the world
  + Conditional regret assumes that a state or some condition is fixed in the environment

### Zero-sum game

* a game where an agent gets a positive reward for completing a task and the other agent receives an opposite negative reward to sum to zero
  + i.e. if an agent scores a goal they get +1 where the opponent agent gets -1

### Stochastic

* basic definition is something that happens randomly and is not fixed

### "Conditioned on the state"

* means that the agent's actions, learning, and decision-making processes are all influenced and determined by the current state of the environment in which it operates

### Value of information

* evaluates how the outcomes of an action may influence the learning agent’s beliefs about other agents, and how the changed beliefs will in turn influence the future actions of the learning agents

### Partially observable environment

* Agent’s are given incomplete information of the environment – this means maybe they are lacking the actions of other agents or they simply are not able to sense their whole environment (sensors on the back of a drone sensing what is behind it might not be there)

### Difference rewards

* Approximates the difference between the received reward and the reward agent i would have received if it had chosen a different action i
  + di = Ri(s,‹ai,a-i›) - Ri(s,‹i,a-i›)

### Aristocrat utility

* Approximates the difference between the received reward and the reward agent i would have received if it had chosen the average action from its policy
  + di = Ri(s,‹ai,a-i›) – E[Ri(s,‹ai’, i,a-i›)]

### Monotonic

* The function is either non-decreasing on its domain or non-increasing on its domain
  + Meaning that if it is non-decreasing it is either increasing or constant at every point on its domain
  + If it is non-increasing it is either decreasing or constant at every point on its domain

### Neural network

#### Input layer

* is referred to the first layer that is multiplying the weights and the inputs

#### Output layer

* is referred to the last layer which gives the output of the network

#### Hidden layer

* is referred to the layers within the neural network which are internal representations

#### Depth

* is the number of layers

#### Width / hidden dimension

* is the number of neurons in a layer

#### Universal approximation theorem

* states that a neural network with a layer of 1 can represent any continuous function

#### Closed-form expression

* A function that can fully express a given problem
  + i.e., a2 + b2 = c2 for the Pythagorean theorem

#### Non-closed form expression (open-form)

* An expression that cannot be explained by basic math operations and is instead a complex set of advanced operations such as differential equations or infinite integrals

#### Vanilla Gradient descent

* A method used for optimization that involves updating parameters in a way that is in the negative direction of the loss function; performs on all training data
  + In layman terms this simply tries to find a minimum of some function

#### Stochastic gradient descent

* Chooses random samples from the data and performs gradient descent on those specific points of data

#### Mini-batch gradient descent

* Take a batch of the training data and performs gradient descent on this batch
  + Between the extremes of vanilla gradient descent and stochastic gradient descent

#### Backward pass

* The process of computing gradients for every gradient backward through the network one time

#### Forward pass

* The process passing outputs forward in the network to get a final output given a set of inputs

### Deep RL

#### Deadly triad

* Combining off-policy learning, bootstrapped targets, and value function estimations can cause the bootstrapped target to estimate to change very rapidly which can lead to unstable optimization

#### Off-policy learning

* The value function that is learned by sampling actions that can be random without taking them from the policy

#### On-policy learning

* The value function is learned from the actions that are taken by the policy given a state

#### Identically and independently distributed (I.I.D)

* Assumes training data is not correlated in any way and that it is pulled from an equal distribution

#### Surrogate loss function

* A loss function that updates the policy parameters

#### Returns

* Returns is the cumulative reward received over time (i.e. the actual cumulative reward received)

#### Value

* Value is the expected cumulative reward (i.e. the prediction by the critic)

#### Utility function

* A function that is conditioned on each agent’s own observation history and action of the agent
  + Q(hi, ai; θ) is the utility function – all utility functions of each agent is jointly optimized to approximate the centralized action-value function

#### Recursive reasoning

* One who considers how their actions might affect others and what others might believe about their own knowledge